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Norm R. Catto

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Résumé de l'article

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MORE THAN 16 YEARS, MORE THAN 16 STRESSORS: EVOLUTION OF A REFLECTIVE GRAVEL BEACH, 1989-2005

Norm R. CATTO*; Department of Geography, Memorial University of Newfoundland, St. John's, Newfoundland A1B 3X9, Canada.

ABSTRACT Mobile Beach, a reflective, moderate-to-high energy, gravel bayhead bar system in eastern Newfoundland, has been influenced by 15 hurricanes and strong winter storms, and at least 9 significant autumn and winter storms between July 1989 and December 2005. Yearly variations in the extent of seasonal ice cover offshore, and snow cover, ice foot development, and freezing of beach sediment, also have shaped Mobile Beach. Vehicle activity and foot traffic have resulted in coarsening, compaction, and steepening. Excavation of a drainage channel through the beach affected sediment supply and transport. Changes in hurricane activity, in the occurrence and impact of northeast winds, and in seasonal ice cover, play a major role in shaping coastal morphology, in conjunction with sea level rise. Variations in the North Atlantic Oscillation are reflected in storm effectiveness and snow and ice influence. Tropical storm and hurricane activity results in substantial modifications to the beach, but the erosional events cannot be correlated with overall variations in hurricane activity. Although Mobile Beach does respond to large-scale regional to hemispheric factors, local factors, including the angle of wave attack, the number of previous events, and anthropogenic activity, play the dominant role here.

RÉSUMÉ *Plus de 16 ans, plus de 16 stress : évolution d'une plage réflective de graviers, 1989-2005.* La plage de Mobile est une plage à forte pente (dite réflective) de graviers, de niveau d'énergie moyen à élevé, située au sud-est de Terre-Neuve. Elle a subi 15 ouragans ou violents orages hivernaux, dont au moins neufs orages d'automne ou d'hiver importants se sont produits entre juillet 1989 et décembre 2005. Les variations annuelles de l'étendue de la couverture de glace au large, la couverture nivale, le développement d'un pied de glace et le gel des sédiments de plage ont également façonné la plage de Mobile. Le passage de véhicules et de piétons s'est traduit en une augmentation de la taille des sédiments, leur compaction et l'accentuation de la pente de la plage. Le creusement d'un canal de drainage a également affecté l'apport et le transport des sédiments. Les changements de l'activité des ouragans, de la fréquence et de l'impact des vents du nord-est et du couvert de glace saisonnier, couplés aux variations du niveau de la mer, jouent un rôle majeur sur la formation de la morphologie côtière. Les variations de l'Oscillation Nord Atlantique se reflètent dans l'intensité des orages et l'incidence de la neige et de la glace. Les tempêtes tropicales et les ouragans modifient substantiellement la plage, mais l'érosion ne peut être corrélée aux variations générales de l'activité des ouragans. Bien que la plage de Mobile réagisse aux facteurs régionaux et hémisphériques d'ensemble, les facteurs locaux, incluant l'angle d'attaque des vagues, le nombre d'événements antérieurs et les activités anthropiques, y jouent ici un rôle clé.

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* E-mail address: ncatto@mun.ca

INTRODUCTION

Analysis of beach dynamics, sedimentology and geomorphology is conducted for numerous purposes, including assessment of response to climate and human-induced stressors. Reflective gravel beaches are highly responsive to both local and regional phenomena and events. Determining the relative influence of these is necessary, both to understand a particular system and to recognize its role as a proxy for assessment of regional impacts of storm events, climate variation, and longer-term climate change.

Repetitive inspection and measurement is necessary in order to capture response to individual events and seasonal changes. Only visiting and investigating a beach system on "bright, sunny, and calm summer days" will not provide a true picture of the dynamics, sedimentology, or geomorphology. Establishing the importance of large-scale regional to hemispheric factors, such as the North Atlantic Oscillation and changes in storm frequency and magnitude, requires detailed observations and assessment of the local factors, including the influence of individual storms and local human activity. Generalizations, even over a small region, will not be valid unless they rest upon detailed site investigations.

STUDY AREA

Mobile Beach is located 40 km south of St. John's (52° 51' W, 47° 15' N), along the exposed Atlantic "Southern Shore" of the Avalon Peninsula (Fig. 1). This beach system was selected for detailed investigation and repeated transect measurement in 1995 due to its demonstrated sensitivity and differential response to storm events between August 1989 and October 1994. Its proximity to St. John's facilitated repetitive investigation. Relatively few people visited Mobile Beach prior to 1995, making it more suitable for investigations than other, more disturbed beaches. In the intervening years since 1995, however, human disturbance has become a greater factor at Mobile Beach.

The 160 m long pebble-cobble-boulder beach forms a concave arc at the head of Mobile Harbour (Fig. 2), flanked by prominent headlands composed of argillite and fine sandstone of the Renews Head Formation (King, 1988). The northern 50 m of the beach is composed of coarse glacially-transported cobbles and boulders, with interspersed areas of exposed bedrock platform. The most active part of the system is the 110 m long, 25-35 m wide pebble-cobble beach at the head of Mobile Bay, fully exposed to the open Atlantic Ocean to the east (Fig. 3).

The landward edge of the beach is flanked by a 5-7 m high flat-topped bedrock ridge, veneered with coarse glacial diamicton less than 1 m thick (Catto, 1994) and supporting *Picea mariana* with maximum ages of *ca.* 50 years. No evidence of storm damage to tree trunks is apparent. The ridge is flanked by two depressions created by fluvial erosion. The southern depression is occupied by Mobile Brook, which enters the sea directly downstream of the power generating station of Newfoundland and Labrador Hydro. The northern depression is occupied by a fen, which is periodically drained by a channel dug by the local landowner. This former outlet of Mobile Brook was impounded by storm overwash sediment, predominantly fine pebbles and coarse cobbles, during the severe storm of January 1966. This outlet had previously been abandoned by Mobile Brook when the stream was diverted for hydroelectric power production and road construction.

OCEANOGRAPHY

The tidal regime is microtidal, as indicated both by observations on site and data from the adjacent Gull Island tide gauge (Fisheries and Oceans Canada, 2005). The modal tidal range at Gull Island is 1.4 m, and isolated observations at Mobile Beach suggest that tidal range here is *ca.* 20-40 cm lower than at Gull Island. Tides are insignificant compared to waves in shaping Mobile Beach.

Off the open Atlantic shoreline, modal significant deep water wave heights throughout the year are 7-8 m (Neu, 1982). The 10-year significant wave height is estimated at 11 m, and the 100-year height is approximately 15 m. Waves up to 30 m high have been recorded by ships off the eastern Avalon coast within recent years (Swail, 1996). Anomalous individual storm waves result in distortions of the 'average' height calculated for significant waves, but the significant wave

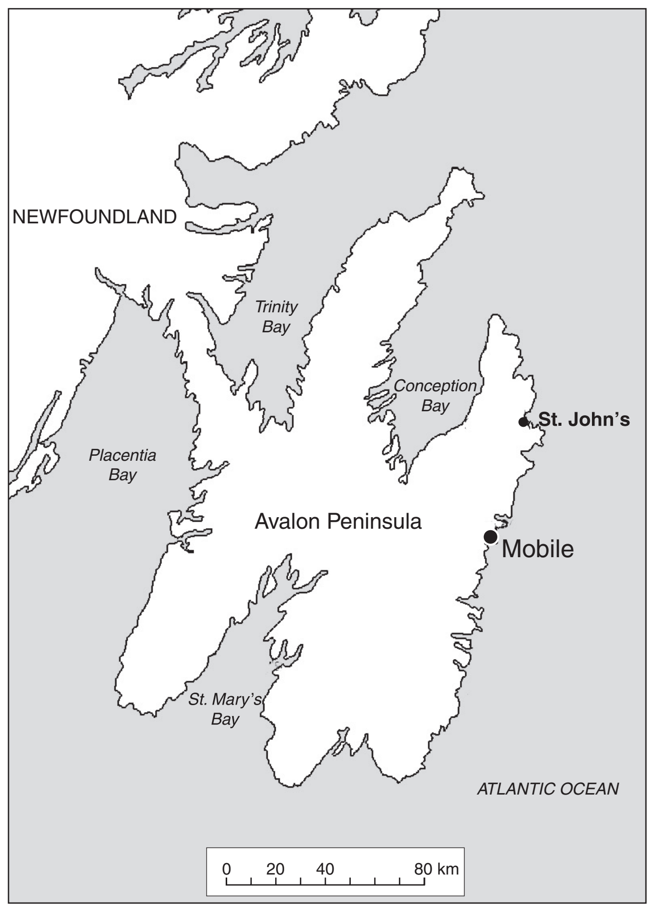

FIGURE 1. Location of Mobile Beach.
Localisation de la plage de Mobile.

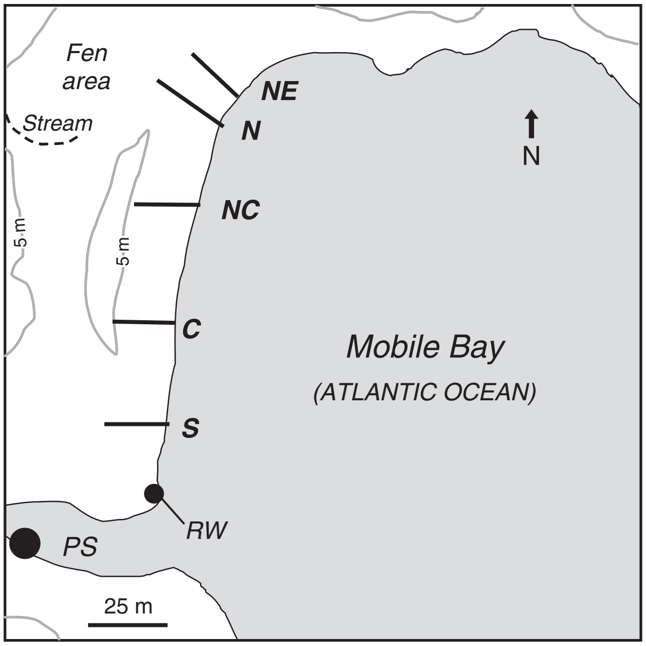

FIGURE 2. Location of transects on Mobile Beach. RW: remains of wharf destroyed in 1966 storm; PS: power station. The 5 m contour as of 1995 is shown.

Localisation des transects sur la plage de Mobile. RW : restes d'un quai détruit par un orage en 1966, PS : centrale d'énergie. Les courbes de niveau sont espacées de 5 m et représentent l'élévation en 1995.

FIGURE 3. Central (foreground) and South (background) Transects, Mobile Beach. The beach slope and tiers of cusps were apparent in April 2005.

Transect central (avant-plan) et sud (arrière-plan) de la plage de Mobile. La pente de la plage et un étagement de croissants de plage sont visibles en avril 2005.

models have a tendency to underpredict extreme storm wave heights (Cardone *et al.,* 1995).

Off the eastern Newfoundland coastline, modal wave periods fall between 6 and 8 seconds. Longer-period waves, *ca*. 12-14 seconds, are associated with decaying ocean swells along the South Coast and the exposed southern margins of the Burin and Avalon Peninsulas (Forbes, 1984).

All wave parameters undergo substantial changes as the waves approach the shoreline of Mobile Beach. Consequently, wave heights and periods measured adjacent to the shorelines, and those which are responsible for modifying the shoreline geomorphology at Mobile differ substantially from these offshore values.

CLIMATE FACTORS

The climate of the eastern Avalon Peninsula is classified as mid-boreal (Köppen-Geiger Dfb). At Mobile, summers are relatively short and cool, with the maximum summer temperature recorded at 27 °C. The August daily mean temperature for St. John's is 17 °C (Environment Canada, 2005), and summer temperatures measured during visits to Mobile Beach do not show any significant difference from those reported for St. John's. Daily mean temperature in February, the coldest month, is approximately -4 °C (Environment Canada, 2005). Winter mean temperatures are 1-2 °C colder at Mobile Beach than at adjacent coastal locations sheltered from northeast winds.

Freeze-thaw cycles are numerous from mid-December to early April, and frost events may occur at any time from late September to mid-May. In south-facing exposed coastal headlands, such as that along the north side of Mobile Bay, several freeze-thaw cycles may occur daily during the early and late winter.

Ice foot development, commonly a major factor in the geomorphology of northern Avalon Peninsula shorelines, is relatively rare at Mobile. Formation of an ice foot largely precludes winter erosion of beach sediments. The southerly extent of persistent ice foot development coincides with the position of the -0.5 °C February Sea Surface Temperature (SST) isotherm (see Cote, 1989). Mean February sea surface temperatures are approximately 0 °C directly offshore of Mobile Beach.

Over the period July 1989-October 2005, true ice foot development at Mobile occurred only during the winters of 1989-1990, 1990-1991, and 1993-1994. Adhering ice coatings 1-2 cm thick on sediments, produced by freezing of precipitation, are common at Mobile Beach. Adhering ice reduces effective erosion during most wave events, although strong waves can frictionally melt the coatings or lift slabs of frozen sediment.

Wind patterns vary seasonally. Easterly and southwesterly winds alternate during the summer and early to mid-autumn. Southwesterly winds are associated with many of the summer and autumn storms, which generally pass over the region from southwest to northeast. Geomorphic changes are associated with strong northeasterly winds, such as the major events of 1966, 1992, and 1994. Easterly winds are commonly associated with late winter and spring events.

The flanking headlands funnel winds into the embayment, making all winds with an easterly component effective as geomorphic agents. The absence of any significant topographic obstructions to the southwest allows strong southwesterly winds to sweep across the Avalon Peninsula, also influencing wave conditions at Mobile Beach. Hurricanes and mid-latitude cyclones tend to approach from the southwest, influencing wave conditions both during their initial impact (southwesterly winds) and as they continue to track offshore towards the northeast (generating storm surge from northeasterly winds).

Although it occurred prior to the start of field research at Mobile, the storm surge of January 1966 requires brief discussion, as it substantially affected the beach system. The event caused more than $1 million damage ($5.1 million equivalent in June 2006) throughout the open Atlantic Southern Shore. To the south of Mobile, the village of La Manche was completely destroyed by the storm surge, although fortunately there were no deaths. At Mobile, a stage and wharf were damaged during the surge. The ruined infrastructure was dismantled following the 1966 storm, although its foundations remain.

METHODOLOGY

Mobile Beach was investigated repetitively between August 1989 and December 2005. During each visit, observations were made of sediment textural spatial distribution, clast characteristics, and morphology. The effects of wave activity and human disturbance were noted. Cusp morphology was measured, with particular attention to spatial variations across the beach system. The longer-term rate of sea level rise was assessed through ^{14}C dating of a submerged *Picea* stump (Catto *et al.*, 2000).

Between July 1995 and October 2005, transects were measured across Mobile Beach at 5 locations, designated as Northeast (NE), North (N), North-Central (NC), Central (C), and South (S), as located on Figure 2. Transects were measured using Emery poles, measuring tape, and Brunton compass, following the techniques outlined by Liverman *et al.* (1994). Elevations along transects were measured relative to mean sea level as datum, correcting for tidal position at the time of measurement. Elevations are accurate to ±2 cm. Each transect was measured between 13 and 17 times (Table I), in order to assess the changes in morphology and sediment volume.

SEDIMENT CHARACTERISTICS AND SUPPLY

Mobile Beach is composed dominantly of pebble and cobble gravel, with lesser amounts of granules and coarse and medium sand (Fig. 4). Glacially-transported boulders form the

TABLE I

*Measurement of transects at Mobile Beach, July 1995-October 2005**

Date	Northeast	North	North-Central	Central	South	Notes
July 1995	X	X	X		X	Initial survey, prior to tropical storm season
November 1995	X	X	X	X	X	Following “Felix”, “Luis”, and “Opal”
August 1998	X	X	X	X	X	Following “Hortense” (1996); no tropical storms in 1997; Limited snow, ice cover in winter 1997 1998
July 1999	X	X	X	X	X	Following April 1999 storm
November 1999	X	X	X	X	X	Following “Gert-Harvey” and “Irene”
August 2000	X	X	X	X	X	Prior to “Michael”
August 2001	X	X	X	X	X	Prior to “Erin” and “Gabrielle”
October 2001	X	X	X	X	X	Following “Gabrielle”
July 2002	X	X	X	X	X	Traffic begins to increase along East Coast Trail
October 2002	X	X	X	X	X	Limited storm activity in Summer-Autumn 2002
October 2003	X	X	X	X	X	Following “Fabian”; 15 000 18 000 annual foot traffic along East Coast Trail
March 2004	X					Following March 2004 storm; preceded storms in March-April 2004
August 2004		X	X	X		Following spring 2004 storms; preceding tropical storm season
November 2004		X	X	X		Following tropical storm season; *ca.* 20 000 annual foot traffic along East Coast Trail
March 2005	X	X	X	X	X	Following January and March storms
June 2005	X		X			Following storm in April 2005
July 2005	X					*ca.* 25 000 annual foot traffic along East Coast Trail
October 2005	X	X	X	X	X	Following mid-latitude storm; no tropical storms impacted Mobile in 2005
Total	17	15	16	14	13	

* Dates of measurement are indicated by an ‘X’. Locations of transects are illustrated on Figure 2.

FIGURE 4. Northeast Transect, showing medium to coarse-grained sand and granules in the intertidal and nearshore supratidal areas, locally veneered by granules and pebbles.

Le transect nord-est, constitué de sable moyen à grossier et de graviers dans les zones intertidale et supratidale, est recouvert localement par des graviers et des galets.

framework of the flanks of the beach. These boulders have not been moved by any wave action since July 1989. The largest clasts moved by storm activity are coarse cobbles, *ca*. 20 cm maximum axial dimension.

Substantial spatial and temporal variation in clast texture is evident. For discussion, the beach is divided into southern, central, and northern sectors. In the central and southern parts of the beach, immediately following storm activity, the subtidal, intertidal, and waterline areas are dominated by coarse pebbles and fine cobbles. Lateral variations in texture are apparent after each storm, but commonly do not show any systematic pattern along the width of the beach in these sectors. Some finer pebbles, granules, and sand are transported by overwash into Mobile Brook landward of the southern sector, and are deposited in the treed fringe landward of the central sector. Most of the finer material is swept seaward. In the mid-beach area, 0.5-1.0 m above mean high tide line in the southern sector and 1.0-1.5 m above mean high tide line area in the central sector, post-storm deposits are dominated by cobbles, with lesser proportions of pebbles and no matrix material. Lateral textural variations show no consistent pattern, and dominantly reflect the configurations of the storm-induced cusps. The uppermost areas of the southern and central areas are dominated by moderately sorted assemblages of medium-coarse pebbles, with few cobbles and with finer material in the interstices. Kelp and rockweed fragments are abundant in the central sector, locally supporting the structure of the cusps, but are rarely found in the southern part of the beach. Overwash deposits in the southern sector consist of poorly sorted sediments, ranging from medium sand to pebbles, and commonly containing cobbles. Organic debris is very rarely present.

After a period of relative quiescence following a spring storm, the texture of the southern and central sectors gradually changes. Along the waterline, and in the intertidal and subtidal zone, sediment is progressively transported from the southern towards the central sector, with lesser transport from the central area towards the north. Simultaneously, granules, fine pebbles, and coarse sand are carried to the southern sector of the shore as bedload by Mobile Brook. The nearshore area of the beach gradually develops a lateral gradient in the southern and central sectors, with sorting progressively increasing and clast size decreasing from the southern to the central sector. In the mid- and upper sectors of the beach, gravitational sorting causes cobbles to move progressively downward, exposing pebbles and granules deposited during events prior to the most recent storms. The uppermost parts of the central sector receive sand and pebbles eroded from the diamicton flanking the beach, resulting in decreased sorting and a net textural fining. In the southern sector, no changes in texture occur unless the beach is disturbed by human activity.

If summer progresses without significant storm activity, and particularly if precipitation is minimal, the beach system laterally aggrades across the Mobile Brook outlet, partially (1994, 1999, 2002-2004) or completely (August-September 1997) blocking it and hindering the migration of brown trout to Mobile Big Pond. During these events, fine to medium pebbles dominate the southernmost subtidal, intertidal, and supratidal sectors of the beach. Granules and sand are transported laterally to the central and northern sectors, resulting in better sorting and overall finer textures. The central sector gradually develops an intertidal and subtidal zone of moderately to well-sorted medium-coarse sand.

Reduced precipitation has the combined effect of reducing erosion of the diamicton veneer backing the central sector, and increasing human use of the beach. The supply of finer pebbles, granules, and sand to the upper part of the central sector is reduced. Infiltration of the finer particles into the uppermost pebble-cobble layers results from compaction induced by human foot traffic. The upper part of the central sector becomes coarser, as the lower part simultaneously becomes finer. In the upper part of the southern sector, human traffic patterns cause compaction to have a lesser effect, and the texture shows less variation.

A summer or autumn storm results in substantial reworking to all parts of the central and southern sectors. Storm waves and surges may induce either northward or southward movement of clasts, depending upon the angle of wave attack. The resulting textural variations can show either northward- or southward-fining patterns. On some occasions, opposed directions of sediment fining were evident in the mid-beach and nearshore- intertidal areas, indicating sequential deposition by waves moving in different directions as the storm gradually decayed. Textures commonly show a range from predominantly granules to predominantly medium cobbles.

Cessation of storm activity in late autumn or early winter can allow snow accumulation, or adhering ice (commonly) or ice foot development (1989-1990, 1990-1991, and 1993-1994). This precludes reworking or erosion of all areas above the high tide line. Windblown sediment deposited on the frozen or snow-covered surfaces gradually infiltrates into the beach during early spring, but the quantity of windblown sediment is very low (less than 1 mm thickness over the beach). During years with no ice cover and minimal snow cover (winter 1997-1998), reworking proceeds throughout the entire season, resulting in removal of sand and granules and coarsening of the beach deposits. In mid-spring 1998, the intertidal zones were dominated by cobbles in both the central and southern sectors of Mobile Beach.

The northernmost sector of Mobile Beach (transect NE) shows differences in texture compared to the central and southern sectors. Prior to January 1966, the northern sector received sediment from the discharge of a small stream reworking glacial diamicton. Subsequently, this stream outlet was infilled by overwash sediment during the January 1966 event, and the area received additional overwash sediment in March-April 2005 and October 2005. The impounded area developed a fen, which despite periodic attempts at drainage by the landowner has remained essentially isolated from the northern sector of the beach. Between July 1989 and September 2001 (Tropical Storm named "Gabrielle"), the subtidal, intertidal, and nearshore supratidal areas were dominated by medium to coarse-grained sand and granules, representing the discharge from the former river system. A systematic decrease in the area of exposed sand above the subtidal zone resulted (Catto and Thistle, 1993; Jones, 1995). Following reworking during "Gabrielle" and subsequent storms (including "Fabian" in 2003), the area of exposed sand decreased further (Etheridge, 2005) and was locally veneered by granules and pebbles. Further storms in March-April 2005 and October 2005 have removed the surface veneer of pebbles and granules, exposing the area of medium sand to approximately the same extent observed in 1994 (Jones, 1995).

In the nearshore and mid-beach areas of the northern sector, sediment consistently fines towards the north. Texture in the mid-beach area ranges from fine cobble-coarse pebble dominated assemblages adjacent to the central sector to fine-medium pebble dominated assemblages in the northernmost part. Although individual storms transport sediment inland by overwash, the net direction of transport is from south to north, and no significant north-to-south transport has been observed. Kelp and rockweed fragments are common throughout all levels of the northern sector. In some instances, kelp fragments compose more than 60% of sediments exposed in cusp walls by volume.

The uppermost part of the northern sector shows seasonal variations in texture similar to those noted for the central and southern sectors. The textural changes are related to human foot traffic in the summer and periodic snow and ice cover in the winter.

Periodic attempts to drain the fen area at the north end of the beach have influenced the sediment texture and geomorphology. Opening of the channel results in a temporary flushing of sand from the back beach area, creating a coarser surface on the beach crest. Sand and fine pebbles disturbed by the digging are transported laterally towards the south, forming a temporary plume in the nearshore. Bank collapse along the newly opened channel results in the injection of pebbles and partially decayed rockweed and kelp into the nearshore area, forming a shallow fan at the channel mouth. Reworking by wave activity results in the redistribution of the sediment towards the south, but the majority of the disturbed material is rapidly retransported to the mouth of the channel. Without significant water discharge from the fen, plugging of the channel ensues within weeks.

Clast shape assemblages vary with position on the three sectors of the beach. Applying the Zingg (1935) shape classification scheme, disc and bladed shapes dominate Mobile Beach, with lesser proportions of equantic clasts. Discs and blades represent 60-80% of the fine pebbles, 75-90% of medium and coarse pebbles, and 85-100% of cobbles near the top of the berms and in the washover fan area. Variations evident over the period 1989-2005 reflect storm activity, as storm waves are capable of transporting larger and more equantic clasts to higher elevations. Equantic clasts are preferentially concentrated in the deepest parts of cusps and at the bases of berms, but do not represent more than 30% of the fine pebbles, 20% of medium pebbles, and 10% of cobbles. Equantic clasts are dominantly granitic, whereas argillites and siltstone/sandstone clasts are bladed and disc-shaped.

The pebbles and cobbles in the upper part of the beach are commonly more compacted by human foot traffic and vehicle use than in the lower sections. This beach is a segment of the East Coast Trail, traversed by approximately 20 000-25 000 people annually since 2002. Increased erosion has been noted along several segments of the East Coast Trail on the northeastern Avalon Peninsula, both in the interior (Reid, 2000) and along beaches (Catto, 2004a).

Following deposition by storm waves, clasts along the berm crest show shingling seaward, with dip angles of 5-10°. Packing is loose, with porosity estimated visually at 30-60%. Upon cessation of storm activity, resumed use of the hiking trail and All-Terrain Vehicle (ATV) traffic results in gradual compaction of the clast assemblage, producing sub-horizontal alignment of the cobbles and larger pebbles, infiltration of the finer clasts, and reduction of effective porosity. Winter snow and ice cover further compacts the assemblage, reducing the effective porosity to *ca.* 10-15% in early spring.

DYNAMICS

Mobile Beach is a wave-dominated reflective system. The laterally confining bedrock walls preclude littoral transport from north or south of the embayment, creating a swash-aligned system. Although lateral transport occurs along the beach, as discussed above, clasts remain within the confines of the embayment. The system is thus effectively dominated by shore-normal transport.

The absence of littoral drift is responsible for the limited amount of debris on the beach, in contrast to other areas on the Avalon Peninsula with comparable adjacent populations (Pink and Catto, 2005). All of the debris on Mobile Beach is apparently of local origin (Catto *et al.,* 2003), although the density of debris (<1 piece/5 m^2) suggests that littering is not a significant problem. However, debris present on the beach system tends to remain in the area for long periods, periodically moving from beach to nearshore and back under the influence of shore-normal transport. Observations of marked clasts indicate that shore-normal transport effectively confines particles within the embayment.

Wave periods measured at Mobile vary between 8 and 30 seconds, indicating substantial increases from the values measured offshore (Neu, 1982; Forbes, 1984). Incident wave heights measured are generally less than those measured offshore, with heights of 2 m associated with the strongest winds when measurement is safe. The distribution of debris and erosional features indicates that peak storm surges reach to *ca.* 8 m above modal sea level.

Waves approaching Mobile Beach are funneled by the embayment bedrock walls, regardless of the initial approach direction driven by the wind. Consequently, waves strike the beach at sharply acute angles in all positions, varying from exactly shore-normal (90°) to a minimum of 70°. The least acute angles of attack occur on either end of the gravel beach, resulting in localized shore-parallel transport.

The relatively steep nearshore bathymetry and the lateral confinement of the embayment combine to produce reflective conditions (Wright *et al.*, 1979), with a substantial proportion of the incoming energy reflected seaward (Baquerizo *et al.*, 1998). Calculation of the surf scaling parameter (Wright *et al.,* 1979) for various observed wave periods and incident wave heights has produced values between 0.01 and 1.3, indicating that reflective conditions are prevalent throughout the range of observed conditions. The development of large cusps by storm waves indicates that reflective conditions also prevail during these events.

The central and northern parts of the beach are marked by stacked tiers of cusps (Fig. 5). A minimum of two tiers has always been present from July 1989 through December 2005, and up to six (partially discontinuous) tiers have been observed. The cusps vary in form along the length of the beach, with the largest, in the south-central segment, being symmetrical, bowl-shaped, and having seaward lips, indicating formation by shore-normal transport in reflective conditions. In the northern segment of the beach, the uppermost cusps are chute-like, indicating that overwashing has occurred, and the barrier crest is as much as 2 m lower here than along the south-central part of the system. The lower tiers of cusps are shallow and asymmetrical, indicating transport parallel to the shore, towards the northeast. Maximum slopes are 25°-30°, and profiles are moderately (following storms) to gently concave (modal condition).

Slopes in excess of the critical angle of repose, up to 51° (Jones, 1995), have been noted in the coarse pebble-fine cobble cusps. Many cusp forms include disturbed kelp and rockweeds, which support the cusp until decay (Fig. 6). The resultant irregularities in form are commonly observed in these cusps. Smaller cusps are strongly asymmetrical, indicating transport along the beach front. In the northerly part of the central segment, all cusps tend to be asymmetrical, indicating transport towards the north.

The lengths of the largest cusps, parallel to the shore orientation, reach 9 m. Maximum widths normal to the beach of 3 m have been noted. Length : width ratios recorded vary from a maximum of 13.5 to a minimum of 1.3, but most cusps have length : width ratios between 4 and 6. Cusp depths, measured from the lowest part of the base to the landward erosional edge in the berm, vary from 0.5 to 5.0 m. Depths of cusps vary proportionally with length, with length : depth ratios ranging between 3.3 and 1.8. The cusps are relatively deep, indicating strong return seaward flow and dominantly shore-normal activity. Width : depth ratios vary considerably, ranging from chute-like cusps with depths greater than widths, to cusps with width : depth ratios of 3.3.

The variations in morphology indicate that the cusps form through a variety of processes. Chute-like forms, with widths less than depths, indicate aligned shore-normal transport with strong return seaward flow. More elongated asymmetrical

FIGURE 5. Cusps formed by reflective wave action, North Transect, March 2005.

Croissants de plage formés par l'action réfléchissante des vagues, transect nord, en mars 2005.

FIGURE 6. Cusp backwall, Northeast transect, March 2005, illustrating dominant disc and bladed, moderately to well-rounded, coarse pebble composition. The importance of rockweed and kelp debris in supporting the cusp backwall is apparent, as the organic detritus comprises approximately 10% of the cusp backwall by volume.

Paroi d'un croissant de plage sur le transect nord-est, mars 2005, montrant une composition de galets grossiers d'angulosité moyenne à faible. L'importance des débris d'algues et d'autres plantes aquatiques pour le soutien des parois des croissants de plage est manifeste, où les détritus organiques y représentent près de 10 % du volume de la paroi du croissant de plage.

forms, with larger length : width ratios and length : depth ratios of 2-3, reflect lateral movement along the beach face. The largest cusps, located at the highest elevations above mean sea level, are of this form. Lower tiers of cusps show varieties in form, ranging from exclusively shore-normal transport to shore-oblique movement, but all are marked by relatively low length : depth ratios.

Reflective cusps can form from either shore-parallel edge waves or as a result of self-organization through shore-normal activity (*see* Werner and Fink, 1993; Allen *et al.*, 1996; Coco *et al.*, 1999; Pittman, 2004). Beaches exposed to edge wave activity on the Avalon Peninsula, including Peters River and Holyrood Pond Beach (Forbes, 1984; Nichols, 1995) and Big Barasway (Boger, 1994; Catto *et al.,* 2003) commonly have cusp length : width ratios in excess of 10, length : depth ratios in excess of 20, and lengths in excess of 20 m. The shore-parallel movement of edge waves along the plane of the water surface would produce cusps with low length : depth and length : width ratios, and with lengths of tens of metres reflecting the subharmonic wavelengths (Inman and Guza, 1982; Seymour and Aubrey, 1985).

At Mobile Beach, the narrowness of the embayment and the acute angle of wave attack preclude the development of effective edge waves. All of the cusps are classified as self-organized, as indicated by their morphology, with relatively low length : width and length : depth ratios, and relatively small lengths.

Once formed by wave action, cusps persist until either eroded by ongoing attrition or reworked by a subsequent storm event. Prior to anthropogenic disturbance in the mid-1990s, storm features created by the major 1966 storm event were still visible at many Southern Shore locations, including Witless Bay (10 km north of Mobile). Along the northern part of Mobile Beach, the crest line formed by the 1966 storm and the overwash fans into the abandoned stream channel remained visible and essentially undisturbed until March 2004, when storm action resulted in erosion on the seaward side and deposition of newer overwash landward of the former crest.

SEA LEVEL RISE

Rising sea level allows waves and storm surges to penetrate further inland, modifying beach morphology and sedimentology. The central part of Mobile Beach is largely confined on the landward side by diamicton-veneered bedrock and the remnants of infrastructure damaged by the 1966 storm event, and thus the beach is unable to respond by migrating inland except at the northern end. The north and south flanks are supported by bedrock. Consequently, sea level rise will produce a steeper, narrower, and coarser beach system over time.

The rate of sea level rise at Mobile Beach can be estimated through inference using the tide gauge records at St. John's, and more directly by ^{14}C dating of a submerged forest including more than 20 *Picea* stumps rooted in terrestrial peat exhumed as a result of storm action in 1994 (Jones, 1995; Catto *et al.,* 2000, 2003; Fig. 7). Unfortunately, these two methods generate substantially different results. Tide gauge records in St. John's Harbour (Fisheries and Oceans Canada, 2005)

FIGURE 7. Rooted *Picea* stump from subtidal area, North transect, excavated to verify its rooted and *in situ* character. This stump was ^{14}C dated at 310 ± 50 BP (GSC-5836).

Souche de Picea, provenant *de la zone subtidale du transect nord, excavée pour observer les racines et les caractéristiques* in situ. *Cette souche a été datée au ^{14}C à 310 ± 50 ans BP (GSC-5836).*

indicate that the current rate of sea level rise is *ca.* 3 mm/yr. In contrast, ^{14}C dating of the outer rings of one rooted *Picea* stump indicated an age of 310 ± 50 BP (GSC-5836). The stump with its subtidal roots, excavated to verify the rooted and *in situ* character, indicates that sea level was at least 2 m lower than present at the time of death. If this ^{14}C date was valid, sea level would have risen at Mobile Beach at a rate of approximately 6-7 mm/yr. This value is more than double that inferred from the tide gauge measurements, and values inferred from elsewhere in southern Atlantic Canada (Shaw *et al.*, 1999; McCulloch *et al.*, 2002).

Three additional sites with tree stumps inundated by late Holocene sea level rise on the Avalon Peninsula have been ^{14}C dated. At Ship Harbour, Placentia Bay, a submerged *Picea* stump yielded a ^{14}C date of 2260 ± 60 BP (Beta-132317), correlative to a calendar age between 2355 and 2130 years ago (Catto *et al.,* 2000). The position of this stump at -2 m asl indicates an approximate rate of sea level rise of 2-3 mm/yr over the past *ca.* 2200 to 2300 years. At Port-de-Grave, Conception Bay, a large *Picea* stump fragment recovered through harbour dredging from -6 m asl produced a ^{14}C determination of 2630 ± 60 BP (Beta-132316), corresponding to a calendar age of 2845 to 2720 years. Assuming that the base of the stump was no higher than -6 m asl at the time of its death, an estimate of between 2-3 mm/yr appears appropriate for sea level rise over the past 2800 years in Port-de-Grave Harbour (Catto *et al.,* 2000). A third ^{14}C determination was obtained in August 2004 from Broad Cove, Avondale, Conception Bay, where more than 40 *Picea* and *Abies balsamea* stumps are exposed in intertidal and subtidal positions. A *Picea* stump from this site produced a ^{14}C determination of 1690 ± 60 BP (Beta-195064), correlative to a calendar age of 260 to 420 A.D. The subtidal elevation of this stump suggests a rate of sea level rise of *ca.* 2-3 mm/yr over the past 1700 years.

It therefore appears most reasonable to assume that the approximate rate of sea level rise along the eastern Avalon Peninsula coastline, including the Mobile area, is currently *ca.* 3 mm/yr. There is no conclusive evidence suggesting that the rate has accelerated substantially over the past *ca.* 2000 years. The value of 3 mm/yr is not incompatible with any previous evidence of sea level rise collected from elsewhere around the Avalon Peninsula, with the exception of the initial ^{14}C determination at Mobile. Recent dendrochronological research (Luckman, 2005) and correlations of ^{14}C dates from marine sediments with dates from coral growth rings and other dating techniques (Yim, 1999; Yim *et al.,* 2006) has suggested that ^{14}C dates in the range of 100 to 400 BP may be inaccurate, particularly when obtained from marine sediments or from samples exposed to marine conditions. Unfortunately, a succession of storms between March 2004 and October 2005 have uprooted or transported all of the stumps formerly exposed in the nearshore subtidal zone at Mobile Beach, temporarily precluding the possibility of obtaining additional ^{14}C dates from the site.

GEOMORPHIC RESPONSE

Mobile Beach is a system with little input from either fluvial activity or littoral drift. It is subject to human foot traffic and ATV activity. Sediment is not mined or removed from the beach, even during efforts to drain the fen behind the northern end. Input of sediment comes from frost wedging of the bedrock, and from shore-normal transport from the nearshore area. Removal of sediment can only be accomplished by return offshore flow under reflective conditions. Consequently, changes in beach height, morphology, and sediment volume reflect the influence of storm and wave activity localized within the cove. Summary data from transects measured across Mobile Beach at 5 locations (Fig. 2) are plotted on Figure 8.

The Northeast Transect (NE) consists of a gently sloping apron in the intertidal area, with a steep pebble-cobble slope with tiered cusps extending from 15-25 m landward of mean sea level (Fig. 8A). The 15-20 m segment exhibited the greatest change over the study period, notably as the result of spring and winter storms in 2004 and 2005. All locations along the NE Transect showed a net loss of sediment between July 1995 and October 2005, primarily in the period following October 2003. The loss of sediment indicates that the NE transect area is dominantly erosional, despite the net northward littoral transport along the beach.

The North Transect (N) showed little net change, with the exception of the highest area of the profile (Fig. 8B). However, the North Transect showed substantial variation throughout the study period, with progressive construction and destruction of cusps. Comparison of the November 1995 profile (following hurricanes “Felix”, “Luis”, and “Opal”), with the March 2005 profile (following a succession of winter and spring storms) demonstrates the tendency of storm activity to remove all lower cusps, producing concave, parabolic forms. In contrast, periods marked by limited storm activity (late 1996-August 1998) result in linearly sloping profiles, with smaller cusps infilled or eroded through gravitational collapse of the back walls (August 1998 profile). Cross-sections with stacked tiers of cusps (October 2001, October 2003) develop as successive, relatively closely-spaced storms rework lower cusps, while leaving upper tiers undisturbed.

The North-Central Transect (NC) was marked by net erosion in the areas 15 m and further landward of mean sea level (Fig. 8C). This transect was substantially influenced by “Gabrielle”, resulting in the erosion of all areas seaward of 22 m distance from the mean high water line, and the formation of a single tier of cusps at this level. Subsequently, the absence of similarly effective storm activity between October 2001 and October 2003 allowed downslope movement of pebbles and cobbles from the “Gabrielle” cusp backwall, resulting in infilling of the base of the cusp and forming the linearly sloping profile measured in October 2003.

Variations recorded in the Central Transect (C) resembled those noted in the North-Central transect (Fig. 8D). Effective erosion of the lower part of this transect resulted from storm activity in winter 2004 and spring 2005.

The South Transect (S) showed the least variation and overall change throughout the study period (Fig. 8E). Fewer measurements were undertaken of the South Transect, due to its apparently greater stability. Clasts along the surface of South Transect commonly showed more chemical staining than those along the other transects, and surface debris remained in place longer. The limited amount of erosion was concentrated in the upper area of this transect.

In summary, all transects were dominated by erosion in the upper areas. The intertidal areas showed small amounts of erosion and deposition, but no consistent lateral pattern was evident, and temporal variations were more significant than any overall change in the lower sections. The period from October 2003 through October 2005 was marked by increased erosion along the Northeast, North, and North-Central transects. These areas are also those most impacted by compression of the gravel framework resulting from foot traffic along the East Coast Trail.

The absence of a consistent linear trend of sediment supply in the intertidal zones of the five transects indicates that longshore littoral transport is not effective in moving sediment. Most sediment is transported by shore-normal waves and gravitationally-driven return flow. Cusps are created by storm wave activity, resulting in temporarily oversteepened slopes and parabolic, concave profiles. After storm activity ceases, gravitational collapse of the backwalls produces a transition to linearly sloping profiles. This tendency is accelerated by remobilization by snowmelt. Human foot traffic along the berm crest line crossing transects NE, N, and NC compacts these clasts, and facilitates gravitational collapse of the cusp backwalls directly below the berm crest line, infilling the lower parts of the cusps and generating linear profiles.

An estimate of the overall changes in sediment volume at Mobile Beach can be made from the profile data. Calculating the net change in height at each position, and integrating the values across the distance between successive transects, produces an approximate value for the change in sediment volume between November 1995 and October 2005 (Table II). Although these volumetric estimates assume that the changes in height can be averaged across the areas between the successive profiles, and are thus approximate, they do indicate the overall pattern of change.

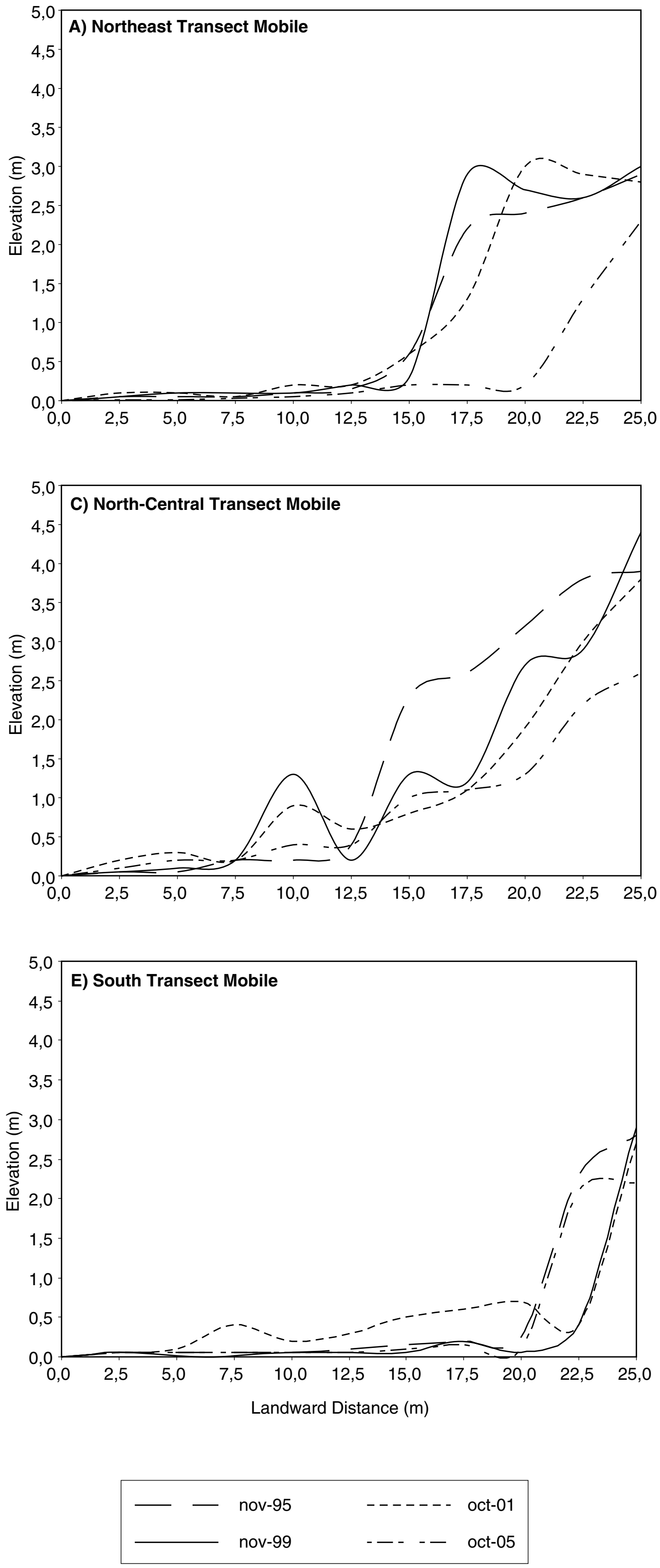

FIGURE 8. Successive profile measurements along transects, at locations illustrated on Figure 2. (A) Northeast transect, (B) North transect, (C) North-Central transect, (D) Central transect and (E) South transect. Datum is mean sea level for November 1995.

Profils successifs d'élévation le long des transects pour les sites illustrés sur la figure 2. (A) transect nord-est, (B) transect nord, (C) transect central-nord, (D) transect central, (E) transect sud. Le référentiel géodésique vertical représente le niveau moyen de la mer en novembre 1995.

TABLE II

*Net change between November 1995 and October 2005**

Beach Segment	0-10 m landward vol. m^3	10-15 m landward vol. m^3	15-20 m landward vol. m^3	20-25 m landward vol. m^3
NE-N	3	-20	-80	-110
N-NC	28	-80	-140	-180
NC-C	37	-200	-270	-240
C-S	20	-120	-160	-150
Total	88	-420	-650	-580

Changes in volume are indicated for selected distances at 5 m intervals landward from the mean sea level position, from 5 m landward to 25 m landward. Datum for elevations is mean sea level, with measured elevations corrected for tidal position. vol. m3 values refer to estimated change in volume for the area extending between adjacent transects (parallel to the shoreline) and between selected distances landward from the mean sea level position in November 1995, determined from the net changes in elevation measured along each transect between November 1995 and October 2005. Beach segments are designated as NE-N (extending from NE transect to N transect); N-NC (North to North Central transect); NC-C (North Central to Central transect); and C-S (Central to South transect). See text for further discussion.

Mobile Beach shows net accretion in the lower 10 m from mean sea level, with greater accumulation in the central area of the beach than at the southern end, and essentially no net sediment flux in the northern area. The total estimated accumulation of less than 90 m^3, however, is a small quantity of material spread across the approximately 1000 m^2 area (mean thickness change *ca.* 9 cm).

Net erosion is apparent in the upper part of the beach, particularly in the North-Central, Central, and South-Central areas. The South and North-East transects show less erosion than the North, North Central, and Central transects. The total estimated erosion of *ca.* 1700 m^3, spread across an area of approximately 1500 m^2, indicates an average lowering of more than 1 m throughout the upper part of the beach between November 1995 and October 2005, with erosion concentrated in the central sector.

REGIONAL AND HEMISPHERIC FACTORS

Beaches along the western coast of the North Atlantic Ocean are subjected to variations in atmospheric pressure and wind systems, as well as yearly changes in the number and intensity of tropical and extra-tropical storms and hurricanes. The study of the response of a particular beach system over time to variations in these regional to hemispheric factors could indicate the degree to which an individual beach can be considered as a proxy for broader environmental changes.

Variations in the dominant pressure system influencing winds and currents in the western part of the North Atlantic Ocean are encapsulated in the North Atlantic Oscillation (NAO), as discussed by Rodwell *et al.* (1999). Since the late 1980s, the Avalon Peninsula has been influenced primarily by the positive phase of the NAO, resulting from the enhanced pressure differential between the Icelandic Low and the Azores High pressure zones. Strongly positive NAO conditions result in severe northerly and northeasterly winds, large wind stresses on the ocean surface, low sea surface temperatures (especially in winter), and extended areas and durations of pack ice and brash ice (Hill *et al.,* 2002). These effects would be most pronounced in the winter months, when the majority of the temperature change has been recorded in Atlantic Canada (Banfield and Jacobs, 1998; Pocklington, 1998). Strongly positive NAO years on the eastern Avalon Peninsula result in the development of coastal icing, jams created by sea ice pushed landward by northerly and northeasterly winds, and ice foot development (Catto *et al.*, 2003; Catto, in press). At Mobile Beach, ice foot development has only occurred in association with positive NAO winters, in 1989-1990, 1990-1991, and 1993-1994.

In contrast, negative NAO conditions, when the pressure gradient between the Azores High and Icelandic Low is diminished, result in weaker northerly and northeasterly winds, and slightly higher sea surface temperatures. The result is that less pack and brash ice is present offshore of the Avalon Peninsula, and the weaker winds are unable to effectively move sea ice to the shoreline. This inhibits icing of the coastline, in combination with marginally higher temperatures on the shore. When negative NAO conditions are enhanced by El-Niño events, as in winter 1997-1998, the result is that beaches remain ice- and snow-free throughout the winter, allowing erosion to proceed throughout the year. At Mobile, the combination of limited snow and ice cover between autumn 1996 and August 1998, combined with an absence of significant tropical storm impact during that period, resulted in steady erosion of the cusp forms, producing linearly sloping profiles. Local steepening of some segments was observed, but other segments declined in slope angle as cusp backwalls collapsed. Overall beach texture coarsened, as finer pebbles and sand was removed by precipitation-induced flow and minor wave action.

Throughout the beaches of eastern Newfoundland, there is a general correlation between positive NAO periods and winter storm erosion, resulting in coarser beaches with steeper profiles (Catto *et al.,* 2003; Catto, 2004b). The observations at Mobile Beach generally agree with this trend, particularly with respect to coarsening of the beach sediment, but there are notable variations in profile response. Lowering of the upper part of the beach system results in redeposition on the lower part, producing an overall flattening of the profile over time, particularly as measured in the summer months prior to the onset of the tropical storm season. However, in early spring, immediately prior to snow and ice melt, the seaward margins of the profiles tend to be steeper, as ice-supported sediments are flanked by shoreline areas subject to frictional heating generated by wave impact. The degree of profile response measured thus depends in part on the time and frequency of measurement. Although Mobile Beach does follow the general trend of response to changing NAO conditions in eastern Newfoundland, local factors appear to play a dominant role in the results.

The effectiveness of any particular storm as a geomorphic agent on an individual beach depends upon the angle of wave attack and the number of previous events during the season (Hayes, 1967). Local factors, however, are also critical. Adjacent beaches can exhibit very different responses to a particular hurricane, as was evident in southwestern Newfoundland beaches impacted by “Gustav” in 2002, on eastern Newfoundland beaches (including Mobile) struck by hurricanes “Bob” (1991), “Luis” (1995), and “Irene” (1999), and on Prince Edward Island beaches affected by “Juan” (2003): beaches separated only by a headland varied widely in the amount of geomorphic response to hurricanes (Catto *et al.,* 2003; Catto, 2004b).

The northwestern Atlantic Ocean has been experiencing an increase in hurricane frequency and magnitude since 1995 (Goldenberg *et al.,* 1996, 2001; Emanuel, 2005; Webster *et al.,* 2005). However, the relationship between changes in hurricane frequency and magnitude, and increases in air temperature or sea surface temperature, is not clear at present (*see* Landsea *et al.*, 1999; Debernard *et al.,* 2002). Although causal links between SST changes and hurricane frequency and strength have been postulated (Sugi *et al.,* 2002; Trenberth *et al.,* 2003; Knutsen and Tuyela, 2004; Trenberth, 2005), other researchers have expressed reservations and recognized uncertainties (Shapiro and Goldenberg, 1998; Pielke *et al.,* 2005; Webster *et al.,* 2005), and consensus does not exist at present. Hurricane frequency in the North Atlantic does not appear to be correlative with air temperature variations in Atlantic Canada (Lewis, 1996; Pocklington, 1998). Regardless of the uncertainty of future changes in hurricane frequency and magnitude in response to climate change, it is apparent that the North Atlantic is currently undergoing a period of increased hurricane activity. This requires a response in emergency preparedness and mitigation strategies (Goldenberg *et al.,* 2001).

The number of hurricanes and tropical storms striking a particular beach is not directly dependent on the overall number of western North Atlantic hurricanes in a year (Taylor *et al.,* 1996; Catto *et al.,* 2003). Although hyperactive years, such as 1995, 1999, 2003, and 2005, would be expected to statistically produce a greater probability of hurricane strikes at each location, the observations at Mobile Beach suggest that a random element is significant. The hyperactive year of 1995 (Goldenberg *et al.,* 1996), produced three significant hurricane events: “Felix”, “Luis”, and “Opal”. These events, in rapid succession, resulted in erosion of the beach and destruction of the previous lower cusp assemblages, and created beach profiles which remained evident through several years of minimal storm activity (1996-1998). In 1999, the simultaneous arrival of “Gert” and “Harvey”, followed rapidly by “Irene”, resulted in substantial erosion and modification at Mobile. In contrast, the hyperactive year of 2003, marked by “Juan”, the most economically costly hurricane in recent Atlantic Canadian history (Canadian Hurricane Centre, 2005a), resulted in no significant hurricane-induced modification at Mobile Beach.

The hyperactive year of 2005, marked by the greatest number of tropical storms ever recorded in a North Atlantic hurricane season (Canadian Hurricane Centre, 2005b), including “Katrina”, “Rita”, and “Wilma”, produced no effects at Mobile Beach: all the storms passed without creating a single significant wave. The only storm-induced modifications at Mobile in the latter half of 2005 resulted from the impact of mid-latitude cyclones, notably in late September and early October.

Years with reduced hurricane frequency and severity also produced contradictory results. The inactive summer 1997 season, the first since 1961 when no tropical storms reached Atlantic Canada, was marked by quiescence. However, years with relatively limited hurricane activity overall in the North Atlantic have been marked by individual storms that have made substantial impacts, such as “Bob” in 1991 and “Gabrielle” in 2001. It is noteworthy that “Gabrielle”, with peak wind strengths substantially below hurricane status upon arrival in eastern Newfoundland, produced greater modifications at Mobile than did the stronger winds of “Hugo”, “Bob”, “Luis”, “Opal”, or “Michael”.

The distance between the Main Development Region for tropical storms in the Atlantic Ocean and the Avalon Peninsula suggests that some element of randomness is involved in storm impact events. The data collected at Mobile indicates that the likelihood of hurricane impact is not enhanced during hyperactive years, although inactive years (1997) result in no impacts. Thus, although tropical storm and hurricane activity does result in substantial modifications to the beach, erosion cannot be correlated with overall variations in hurricane activity.

A complicating factor in assessing the role of storm activity is the modification engendered by late winter and spring storms. At Mobile Beach, these events have had a successively greater effect in recent years, with the storms of early 2004 resulting in modification of beach features that had remained largely undisturbed since 1966. The effectiveness of these storms is related to NAO variations, but also reflects the amount of pre-storm disturbance during the preceding late summer and autumn. The increase in erosion resulting from the winter and early spring storms has coincided with increased foot traffic during the previous summers and autumns along the East Coast Trail. In contrast, some previous winter (“Saros” event, December 1995) and spring storms (“Storm of the Century” or “Perfect Storm”, March 1993) produced limited or no modification at Mobile.

CONCLUSION

The observations at Mobile over the 16 years between July 1989 and December 2005 indicate that the beach as been subjected to far more than 16 stresses. Individual wave and storm events have combined with ongoing sea-level rise (*ca.* 3 mm/yr) since the mid-Holocene, and steadily increasing anthropogenic pressure in recent years. Erosion has increased in the upper part of the beach system, and compensating deposition in the lower areas and intertidal zone has not been sufficient to maintain the overall volume of sediment. Over time, Mobile Beach is becoming coarser in texture, narrower as sea level rises, and apparently less stable as storm activity, notably in winter and spring, combined with human foot traffic, results in enhanced profile modification.

The response to events at Mobile Beach, in conjunction with other observations throughout the period 1989-2005 in several locations in Atlantic Canada, indicate that no single beach can serve effectively as a proxy to assess the overall impact of climate variation. Variations in the NAO are reflected in storm effectiveness and snow and ice influence. Tropical storm and hurricane activity does result in substantial modifications to the beach, but erosion cannot be correlated with overall variations in hurricane activity. Local factors, including the angle of wave attack, the number of previous events, and anthropogenic activity, are dominant.

Individual beaches throughout eastern Newfoundland exhibit different responses to similar regional stresses, reflecting individual, local, often non-replicated circumstances. In this sense, Mobile has a distinctive personality.

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